

Multi-Beam Phased Array Antennas

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Abstract

Many of NASA's future missions require multiple accesses to work together as a single system. To accomplish these missions, multi-beam phased array antennas are required to communicate between satellites flying in fixed formation. In this paper, a comparison of different multi-beam systems will be given followed by detailed discussions of the lens array architecture and test results.

Introduction

NASA has planned as many as 39 science missions over the next twenty years to study the origin of the universe, the Sun, the Earth, and other neighboring planets [1]. Many of these missions require multiple assets to work together as a single system. For example, Stellar Imager will require many satellites in a centralized formation flying, and the Mars mission will use multiple rovers, probes and satellites. To accomplish these missions, multiple, steerable beam antennas are required to collect diverse scientific mission data from formation-flying spacecrafts.

This paper concerns with the development of a multi-beam lens array antenna for crosslink communications between satellites in tight formation. The application considered requires several simultaneous beams at different angles with each capable of dual frequency and dual polarization. The angle of each beam can be fine-tuned of about 5 degree around the fixed positions by amplitude controls of the feed elements. This allows pointing correction with satellites slightly out of formation. For feasibility demonstration, a 56-element planar discrete lens array, space-fed with two small array feeds along the focal arc, has been built and tested through collaborative efforts with the University of Colorado. In the paper, a comparison of different multi-beam antenna systems will be given followed by detailed discussions of the lens array architecture and test results.

Comparison of Multi-Beam Antenna System

Multi-beam antenna systems can generally be divided into three basic classes: reflector, phased array and lens. For multi-beam applications, the most serious

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problem in a reflector antenna is the aperture blocking by a cluster of feeds, which contributes to large blockage losses. Further, reflector antenna suffers from coma and spherical aberrations, and therefore is not suitable for producing multiple beams [2]. The various aberrations greatly limit the scan range of the reflector to only a few beamwidths (typically about 10°). Compensation of aberrations using step zoning and reactive surface loading is difficult and generally adds cost, weight and volume to the antenna system. Reflector antennas often achieve beam steering by mechanical means; thus have size, weight and life-cycle cost disadvantages particularly for space applications. In recent years, reflectarray, a planar version of the reflector, has been considered as substitute for the reflector antennas. Reflectarrays are fabricated using standard PCB technique, and thus have cost, size, and weight advantages over solid reflectors, especially for implementation in space. Another advantage is that the back is accessible for interfacing with the aperture and cooling. There are works currently going to insert phase shifters in the radiating elements of the reflector to achieve beam scan. For multi-beam applications, reflectarrays still face the same blockage and aberration problems as the reflector antennas.

Using active phased array to generate multiple beams has long been in the minds of many researchers. In addition to compact size, light-weight and lower life-cycle cost, active phased arrays can achieve beam agility, diversity, reconfigurability, and adaptivity to complex signal environments. Insertion of microwave monolithic integrated circuits (MMIC) technology into antenna systems using low power and low noise amplifiers in close proximity to the radiating elements also offers significant improvement in the array transmit efficiency, receive system noise figure, low sidelobe level and overall array reliability through graceful degradation. Based on hybrid approach, a Ka-band 4x4 active subarray module of dimensions 3.2 cm x 3.2 cm x .75 cm has been demonstrated by NASA/Texas Instruments in 1994. The active array module delivers 75 watts effective isotropic radiated power (EIRP) with 1990 device technology, and using the state-of-the-art device and manufacturing technology, has the potential of delivering 750 watts EIRP [3]. Since then, progress in active phased array has been in stagnation due to high cost, and problems associated with high density device integration and heat removal. Besides high cost and complex array architecture, excess RF losses in the corporate (or Butler matrix) feed networks and phase shifters also contribute to very low antenna efficiency, making the active array unattractive for multi-beam applications. A schematic of an active phased array is shown in Fig. 1. To generate multi-beams, multiple beamforming networks on separate layers are required, increasing the already complex array architecture multifold.

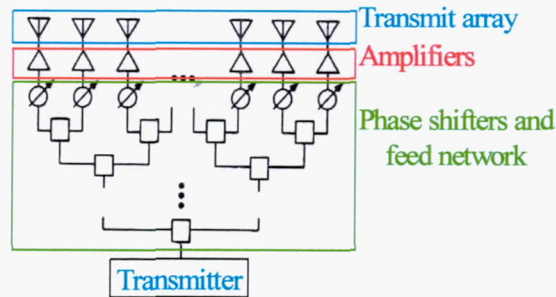
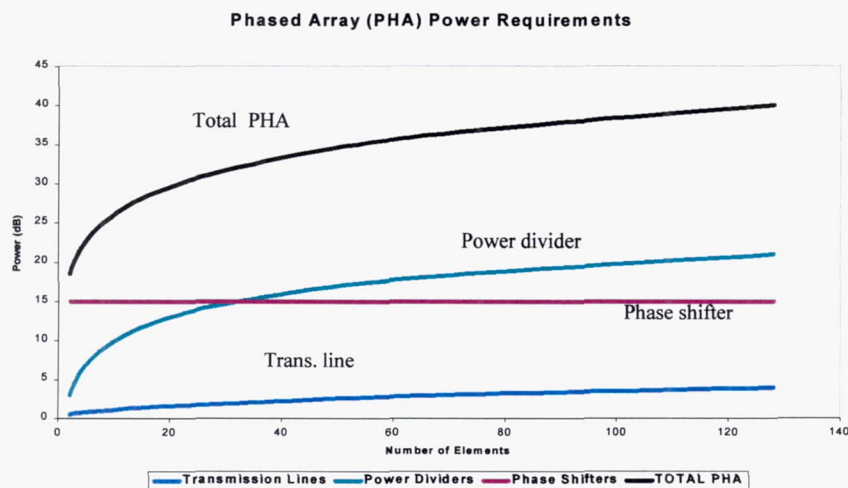
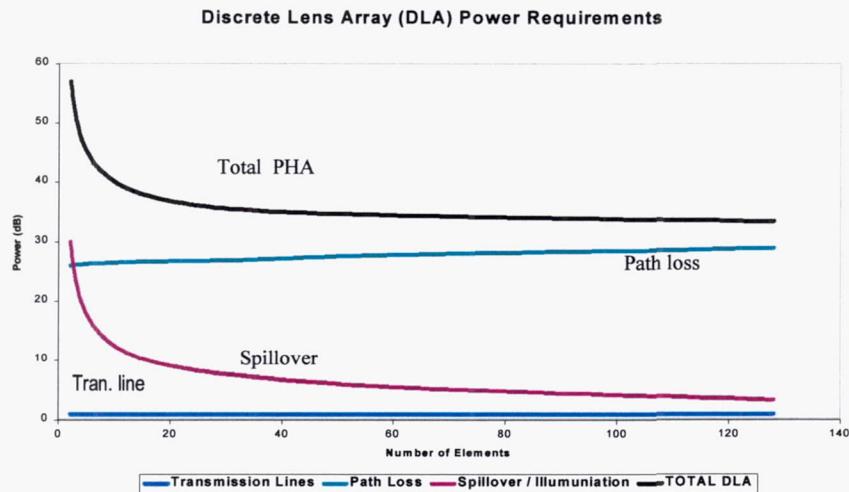


Fig. 1. Schematic of an active phased array

An important advantage of a discrete planar lens array is the simplicity in the feed network. The spatial feed allows a multi-beam configuration with only minor modifications in system design, avoiding the high complexity of a multi-layer corporate feed network as required by the PHA. Since the antenna is fed spatially, there is no RF losses associated with a corporate (or Butler matrix) feed network of a phased array. Consequently, higher efficiency can be achieved resulting in lower power requirement. Fig. 2 shows the input power requirement for a phased array with corporate feed network (PHA) and for a planar discrete lens array (DLA), assuming same EIRP from both arrays. Unlike phased arrays where feed loss increases with array size, feed loss in a lens array with more than 50 elements is nearly independent of the number of elements. The difference in losses is attributed to different loss mechanism in the two arrays. The main losses in the PHA are in the transmission line, power divider and phase shifters which depend



(a)



(b)

Fig. 2 Power requirement as function of number of elements for (a) phased array (PHA) and (b) discrete lens array (DLA)

on the number of elements, while the most significant source of loss in the DLA is the path loss in free space that increases only negligibly with the lens size. The spillover losses improve with the size of the DLA, and the transmission line loss is generally small because of short lengths. Moreover, unlike the lossy and heavy dielectric or metal-plate lenses, planar lens arrays are fabricated using standard PCB technology, making them lightweight, easy to manufacture, and easy to optimize for large scan angles [4]. The radiating elements on the feed-side and radiating-side of the lens can be easily designed for dual frequency and dual polarization operation, thus greatly extending the system capability. Compared to reflectarrays, the DLA does not have the feed blockage problem, and is less sensitive to phase errors introduced by element and feed position variations.

Dual-Beam Discrete Lens Array Design

The basic multi-beam DLA architecture for transmission is shown in Fig. 3. The DLA consists of two arrays with transmission lines connecting corresponding radiating elements on both sides through coupling slots. The multiple beams are obtained with multiple spatial feeds placed along a focal surface on the feed side of the array with each feed position corresponding to a beam in a different direction. In general, four geometric degrees of freedom can be applied in lens

radiating-side surface, (3) relative position of the elements in the two surfaces, and (4) the length of the transmission line joining corresponding elements in the two surfaces. The planar discrete lens described in this paper uses two degrees of freedom, namely (3) and (4), to achieve good off-axis focusing with two perfect focal points lying on a focal arc or with a cone of best focus [5]. In the design, the transmission lines are of different electrical length for each element to provide proper phase delays for equal path length from the feed to each element on the radiating-side of the lens. The larger delay is at the center element to mimic an optical lens, i.e. thicker in the center and thinner in the periphery. The radiating side array is designed the same way as with traditional array where the

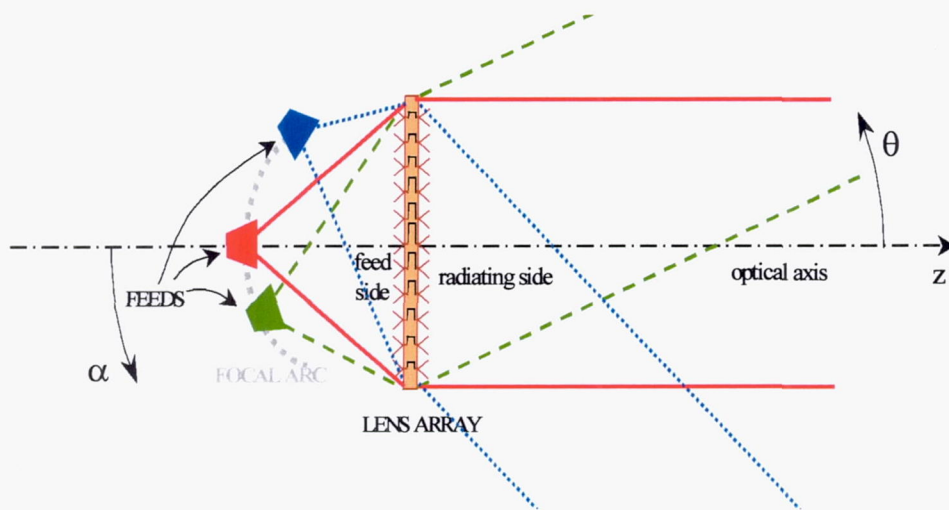


Fig. 3. Schematic of multi-beam transmit/receive lens array with 3 beams :
 α - angle the feed made with respect to the optical axis, θ - scan angle

spacing and type of element is chosen in accordance with performance specifications such as grating lobes, sidelobe levels and beamwidth.

Antenna element design : Fig. 4 (a) shows a dual-frequency patch antenna for the lens array. The antenna, fabricated on 15 mil thick substrate with $\epsilon_r = 6.15$ (Rogers 6006TM), is designed to radiate two orthogonal linearly polarized waves at 25.4 and 27.4 GHz. Quarter-wave transformers are used to match the antenna to 50 Ω transmission lines, which are used to connect the feed-side patch with the

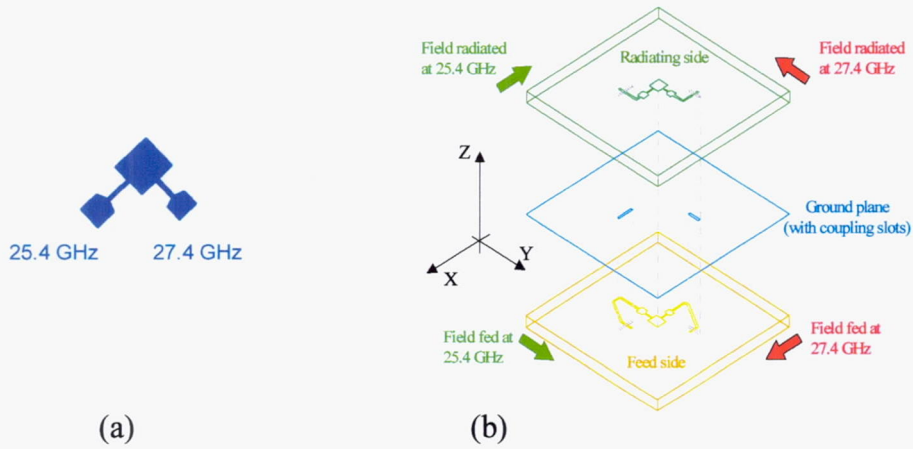


Fig. 4. Schematic of (a) a dual-frequency patch and (b) 3-D view of one element showing slot coupling and orthogonal polarization between the two arrays

corresponding radiating-side patch through coupling slots in the ground planes. As indicated in Fig. 4 (b), the polarization of the feed-side and the radiating-side patches are orthogonal to each other to improve polarization isolation between the two arrays. Fig.5 shows the measured and simulated results for the cross talk and matching of four different antenna elements (A1, A4, A5, A6) in the array.

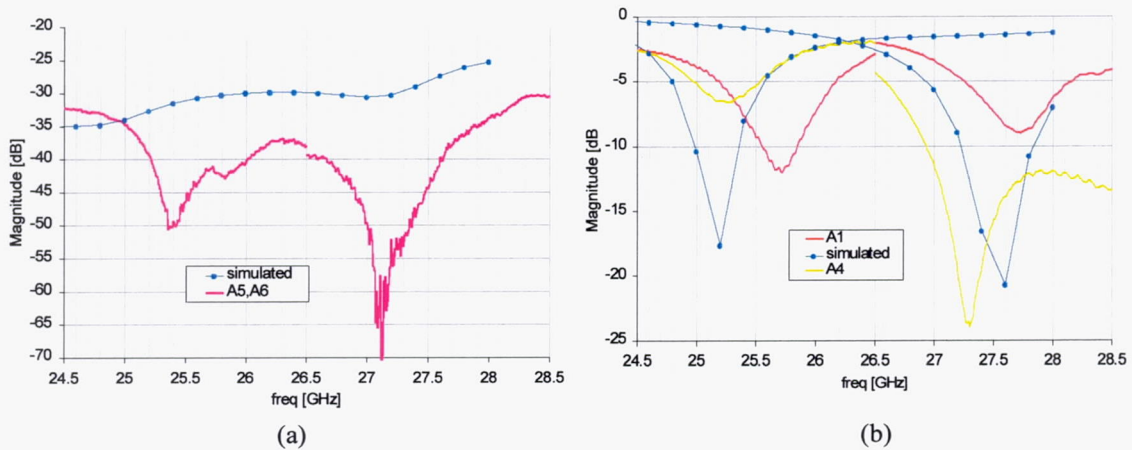


Fig. 5. Measured and simulated cross-talk (a) and matching (b) at the two feeds at the two feeds for different elements in the array

Lens design : The dual-beam discrete lens array was designed for cone of best focus at $\theta = \pm 30^\circ$ with symmetry around the z-axis ($\theta = 0^\circ$) [5]. Both the feed-side and the radiating-side arrays consist 56 elements, which are arranged in

triangular lattice with $0.66\lambda_0$ horizontal spacing and λ_0 vertical spacing. The spacing will provide enough space to fit the antenna module and still avoid grating lobes for feed placed at $\theta = \pm 30^\circ$. By imposing two degrees of freedom in the design creates displacements in the relative position of corresponding elements in the two arrays. As a result, a transmission line layer buried between the two arrays is required to connect the feed-side element with the radiating-side element through coupling slots. Fig. 6 shows the cross-sectional view of the final

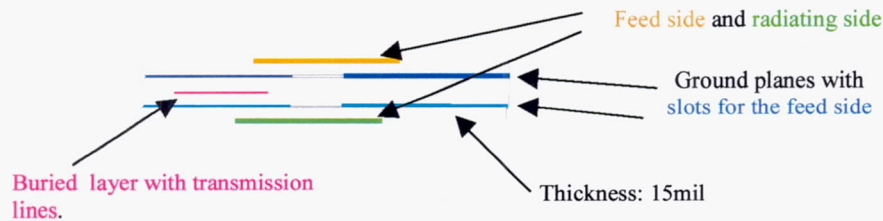


Fig. 6. Cross-sectional view of the multi-layer DLA structure

DLA structure which is made up of five metal layers and four dielectric layers.

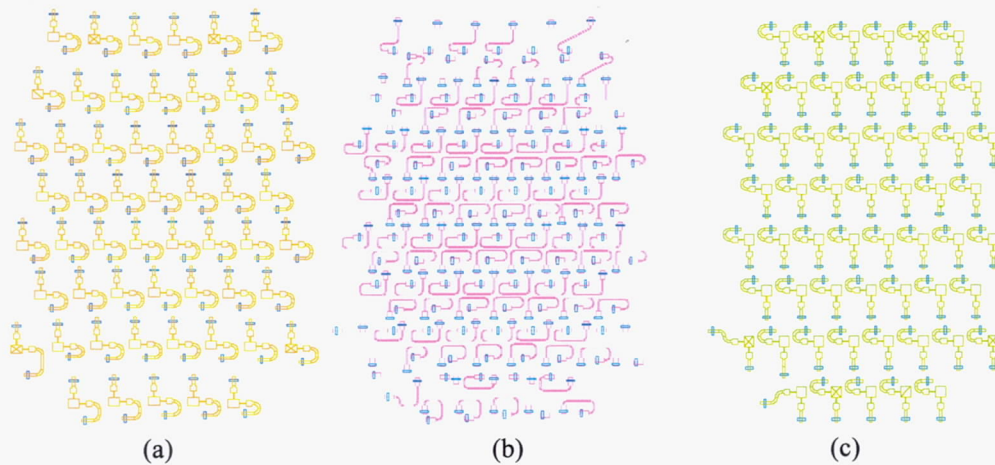


Fig. 7. Layout drawings of the metal layers: (a) feed-side with slots, (b) buried layer with transmission lines and slots, and (c) radiating-side with slots

Fig 7 displays the layout drawings of the three metal layers. The planes with slots are ground planes where only the slots are represented in the drawing for clarity.

Fine beam steering using amplitude control: Due to the fact that the lens array behaves like a discrete Fourier Transform, amplitude variation at the feed in the image plane correspond to phase steering of the radiated beam in the far field. This is in contrary to the conventional phased array approach where phase steering is used to achieve beam steering. Fine beam steering can be achieved with a single variable gain element of a 2-element array feed. Fig. 8 shows main-lobe steering of $\pm 2.5^\circ$ with normalized amplitude variation from 1 to 0.1 on the feed.

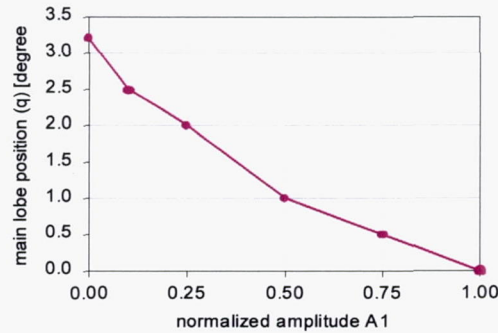


Fig. 8. Simulated main-beam position with amplitude variation for a 2-elment array feed

Experimental Results

The 56-element prototype lens, fed spatially with two array feeds at $\theta = \pm 30^\circ$,

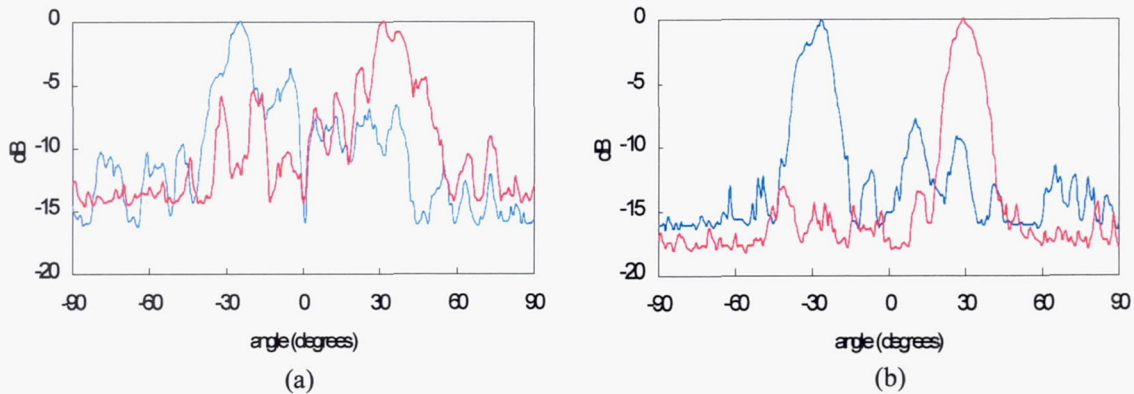


Fig. 9. Measured dual-beam radiation patterns at (a) 24.7GHz, and (b) 26.7 GHz

was fabricated and tested in a far field antenna range. Each array feed has two input ports for transmit or receive signals at the two design frequencies of 25.5 and 27.5 GHz. Fig.9 shows the measured radiation patterns at 24.7 and 26.7 GHz.

The patterns exhibit two distinct beams at the $\pm 30^\circ$ scan angles. However, there is a shift of about 3% in the operating frequencies with respect to the design frequencies of 25.5 and 27.5 GHz due to fabrication tolerances. Also, it is noticed that the lower frequency patterns have unusually high sidelobes that are partly caused by reflection from the array fixture and from an array feed with poor matching and isolation characteristics. Covering all edges of the array housing with absorber did eliminate some reflections, and using an open end waveguide as feeds produced significant improvement in the sidelobe levels as shown in Fig. 10.

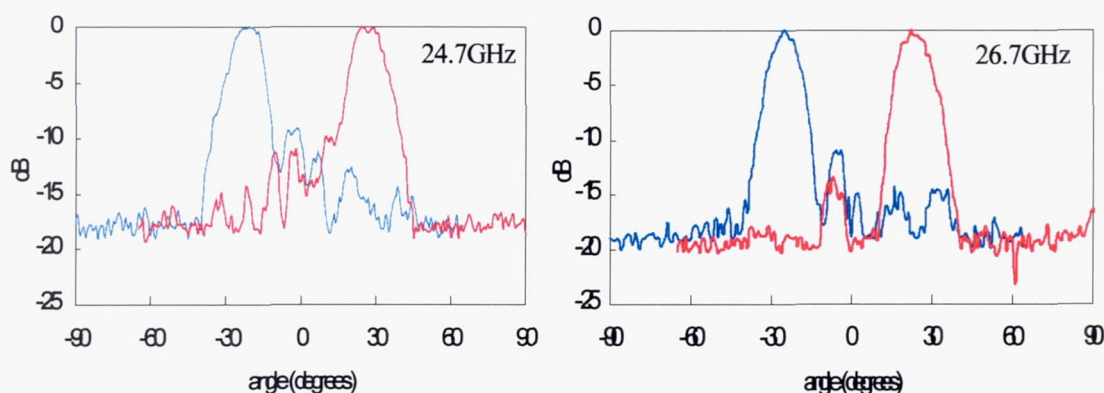


Fig. 10. Measured radiation patterns at the two frequencies for the lens with open waveguide feed.

Summary

Planar discrete lens array features low cost, low loss, light-weight, and simple structure as compared to other types of multi-beam array systems. In the paper, design and measured results of a dual-beam, dual-frequency DLA have been presented. Further, small angle steering with amplitude variations of the feeds avoiding the use of phase shifter has been demonstrated.

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